Investigation of Coastal CDOM Distributions Using In-Situ and Remote Sensing Observations and a Predictive CDOM Fate and Transport Model

Nickitas Georgas, Wei Li, and Alan F. Blumberg
Center for Maritime Systems, Davidson Laboratory
Stevens Institute of Technology
Castle Point on Hudson
Hoboken, New Jersey, 07030
phone: 201-216-5218 fax: 201-216-8214 email: ngeorgas@stevens.edu

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LONG-TERM GOALS

Our long-term goal is to interprete chromophoric dissolved organic matter (CDOM) sources, distributions, and dynamics in and around the NY/NJ Harbor Estuary, with a focus on significant freshwater events, through the creation of a robust, deterministic, high-resolution, four-dimensional, predictive model of CDOM fate and transport, validated against in-situ and remote sensing observations.

OBJECTIVES

An existing four-dimensional hydrodynamic and CDOM source tracking model was significantly updated and compared against a) concurrent datasets of *in situ* (EcoShuttle) CDOM observations available for the New York/New Jersey Harbor and, b) satellite-derived (SeaWiFS) surface CDOM distributions for the Harbor and its New York Bight Approaches (Bight Apex). The New York Harbor Observation and Prediction System (NYHOPS), a hydrodynamic/CDOM forecasting model incorporating CDOM fluorescence source strengths and first-order decay through photodegradation, was updated to a new high-resolution version shown to better capture the relevant hydrodynamic scales and associated CDOM sources and transport. The NYHOPS CDOM fate module was singificantly changed to include a more robust and deterministic bio-kinetic formulation of CDOM absorption loss due to photobleaching. Existing high-resolution local observations of CDOM fluorescence, absorption and other related variables, were used to locally calibrate the NYHOPS bio-kinetic module. CDOM distributions based on NYHOPS were compared to both the in-situ observations and SeaWiFS-derived spatial distributions, to continue interpretation of the CDOM data and facilitate an understanding of the processes that control CDOM distributions in estuarine and coastal waters.

The goal of this project is to interpret CDOM distributions in the New York/New Jersey Harbor and New York Bight system by comparing complementary information from the NYHOPS/CDOM fate and transport model, *in situ* data, and satellite-derived imagery. The objective is to put the CDOM distributions and sources in perspective, through comparison of multiple data sources. We focused

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on significant freshwater events, testing the hypothesis that CDOM originating within the NY/NJ Harbor estuary can dynamically influence CDOM distributions in the NY Bight.

APPROACH

In 2005, ONR sponsored a dual two year effort involving both observations and dynamic modeling to investigate CDOM distributions and dynamics in New York Harbor and vicinity. A multitude of data in tributaries and embayments inside the Harbor (Chen et al 2005 2006) were collected. The collections inside the harbor were used to identify CDOM source strengths, while the ones outside the harbor were used to follow the transformations of CDOM as it is transported down the New Jersey Shelf and diluted with resident sea water. With regard to the Hudson tributaries, CDOM endmember concentrations were found to photodegrade or biodegrade by 30% in incubation experiments (Chen et al 2006). At the same time, an ONR-funded dynamic modeling effort was underway at Stevens Institute of Technology (Stevens), supported by the abovementioned observations (Blumberg 2007). The objective there was to develop a capability for incorporating CDOM source strengths and chemical processes into the operational 4-dimensional hydrodynamic New York Harbor Observation and Prediction System (NYHOPS). Satellite data can also be used to infer marine constituents in coastal waters.

In this project, we significantly updated the NYHOPS CDOM module (Blumberg 2007) to use an improved NYHOPS hydrodynamic module with wave-current interaction, more robust wetting and drying, steric effects, 2D surface heat fluxes and other upgrades (Georgas *et al* 2009), and an alternative and complementary description of CDOM photodegradation and, importantly, CDOM biomass and light absorption. As part of this work, we setup and run the new high-resolution NYHOPS/CDOM model from June 1st 2006 onward. We then assessed the model skill for water level, current velocity, temperature, salinity and significant wave height. With regard to CDOM chemical kinetics, a) we included and modified based on our analysis of local data the CDOM photolysis-related loss terms from the ECOSIM 2.0 formulation (Bissett 2005 and FERI 2004) and included diffuse light attenuation in the water column based on incoming radiation and dynamic color feedbacks, b) we included estimates of absorption provided by localized fluorescence to absorption curves (Wei Huang, pers. comm.), c) we improved the photolysis rate equations and included light attenuation in the water column, and d) we expanded the limited original estimates for CDOM end-members to the full river and water treatment plant network of the high-resolution NYHOPS system, in terms of both CDOM fluorescence and biomass based on extensive literature search, and e) for the riverine end-members in particular, automatic baseflow separation (Arnold *et al* 1995) was coded for *hourly* streamflows and used to calculate distinct runoff and baseflow loading rates (Figure 1).

We acquired and analyzed the CDOM observations made by the University of Massachussets, Boston team led by Drs. Chen and Gardner inside NY/NJ Harbor waters in 2006 and 2007. We extracted information on the shape of the CDOM absorption spectra and quantified correlations with CDOM fluorescence. We then used this data to: a) derive photolysis-related coefficients needed in the new alternative CDOM loss equations, and b) compare to the new NYHOPS/CDOM model results mentioned below. Significant freshwater events were identified in terms of their influence to CDOM distributions in the Harbor and, especially, the Bight Apex. Two events that were certainly significant in the 2006-2007 time span were the near-500-year flood in upstate New York in the end of June 2006, and the significant New Jersey “tax day” flooding event in April 2007. Significant non-freshwater events, for example Tropical Storm Ernesto (September 2006),

were also looked at. We collected and stored SeaWiFS radiative spectral images for both the events mentioned above as well as the in situ sampling periods. We processed the images for clouds, and used standard SeaDAS algorithms to estimate CDOM absorption, chlorophyll concentrations, and backscatter. We finally looked at correlations of SeaWiFS-inferred and NYHOPS-predicted absorption to interpret CDOM distributions in the New York Harbor and Apex, and assess the significance of NY-Harbor-originating CDOM to CDOM concentrations in the Apex.

WORK COMPLETED

The new version 3 NYHOPS hydrodynamic model was run backwards to June 2006, and extensive validation is nearly complete against water level, current, temperature, salinity, and wave observations collected in more than 100 stations (Georgas and Blumberg 2009, in preparation).

There are four systems considered in the redesigned NYHOPS CDOM module, based on the RCA3 (Raw-Column-Aesop version III) modular FORTRAN code:

System 1: Allochthonous CDOM fluorescence

$$\frac{d[CDOM]_F}{dt} = -K_{ph} * [CDOM]_F * \Lambda \qquad \textbf{(1)}$$

System 2: Allochthonous CDOM concentration

$$\frac{d[CDOM]_T}{dt} = -\alpha^*(410) * (RtUVDOC + RtUVDIC) * [CDOM]_T * \Lambda \qquad \textbf{(2)}$$

System 3: Labile DOC created by Allochthonous CDOM photolysis

$$\frac{d[LDOC]_T}{dt} = +\alpha^*(410) * RtUVDOC * [LDOC]_T * \Lambda \qquad \textbf{(3)}$$

System 4: DIC created by Allochthonous CDOM photolysis

$$\frac{d[LDIC]_T}{dt} = +\alpha^*(410) * RtUVDIC * [LDIC]_T * \Lambda \qquad \textbf{(4)}$$

$$\Lambda = \frac{E_d(0^-) * \exp\left[\int_{0^-}^{z^-} K_d(300,z)dz\right]}{E_d(0^-)^S * \exp\left[\int_{0^-}^{z^b} K_d{}^b(300,z)dz\right]} \qquad \textbf{(5)}$$

$$K_d{}^b(300,z) = [\alpha_{CDOM_{l+r}{}^b}(410)]\exp\left[-S_{UV} * (300-410)\right] + K_{d\_w}(300) \qquad \textbf{(6)}$$

$$\alpha(410) = \alpha^*(410) * [CDOM] \qquad \textbf{(7)}$$

Localized values for the coefficients were based on our analysis and Dr. Huang's ECOShuttle data.

Light absorption by CDOM at 412nm was inferred from satellite reflectance measurements using four available algorithms. These independent absorption estimates and their ensemble mean were then compared to CDOM absorption at 410nm as estimated through equation (7) [results section]

from the CDOM biomass distributions simulated in the NYHOPS CDOM model. 20 satellite passes between June and November 2006 and 6 satellite passes after the April 2007 flood event were analyzed.

RESULTS

Figures 3-5 show lagrangian comparisons of transient hydrodynamic fields sampled during the ECOShuttle expeditions and NYHOPS hourly predictions. It is interesting to note the differences in salinity between the 2006 and 2007 surveys; the later was greatly influenced by the significant "Tax Day" flooding event that lowered the salinities of much of New York Harbor and surrounding oceanic waters for many days after the event occurred. Overall, the NYHOPS model captured the means and gradients of the observed temperature and salinity spatio-temporal variation with great skill; the correlation coefficient between model and observations was 0.876 in 2006 and 0.925 in 2007. The illustrated results imply that the advection and diffusion transports linked to the CDOM module, run for the same 3-year period, were quite accurate.

The comparison of the NYHOPS CDOM model to the along-track observations made in 2006 and 2007 by the UMASS Boston team in the waters of the NY/NJ Harbor Estuary is summarized in Figures 6-7. Note that the CDOM model transports and output were provided hourly, and observed intra-hour variations in the transient fields may contribute to the apparent error variation. Overall, the NYHOPS CDOM model reliably predicted allochthonous CDOM in receiving harbor waters in both the October 2006 survey (correlation coefficient = 0.953) and the April 2007 survey (correlation coefficient = 0.670), explaining 86.4% of the overall variability in the observed data (Figure 6). The two sampling periods deferred markedly. October 2006 showed a higher variability in CDOM data, both collected and simulated, while the "tax day" 2007 event appears to have produced low CDOM concentrations, diluted by freshwater runoff (Figure 7). The worst performance in the model was on April 17 2009 in the Hackensack River with the model unde-rpredicting CDOM by about 29.0% (Figure 8). This is most likely due to erroneous streamflow records provided to the model as the Hackensack River rose quickly to a record level, making its rating curve obsolete, and submerging its gage (see Figure 1). Otherwise, the model is within 20% of the observations, with the least relative error observed in the Passaic River (Figures 8 and 9). Overall then, the NYHOPS CDOM model is a good predictor of CDOM fluorescence distributions within the waters of the NY/NJ Harbor Estuary.

Overall the four standard satellite retrieval algorithms show great variability, both in the spatial coverage of algorithm convergence (absorption retrieval, given cloud cover, sun glint, stray light, high tilt corrections and limitations), and in the magnitude of their estimates. This variability is especially pronounced at the fringes of the satellite retrievals, and, in the area of primary interest to this study, the lower New York Harbor and the NY Bight Apex, where possible impact to light absorption from allochtonous CDOM exported from the estuary into the coastal ocean, especially during major freshets, has been hypothesized. However, even in more open water areas, the day-to-day variability of individual algorithms is sometimes high, pointing to either significant uncertainty in the retrievals, or to potential fluctuations of autochthonous (not modeled) CDOM from phytoplankton diurnal cycles, or both.

The Sep 3 and 4 2006 retrievals (Figure 10) in particular are interesting, because they coincided with the passage of Tropical Storm Ernesto over the NYHOPS region (http://www.stevens.edu/maritimeforecast/google/TS_Ernesto_NYHOPS_Vs_III_Nickitas.zip). The

satellite retrieval of Sep 4 2006 points to the possibility that intense vertical mixing from the storm might have surfaced deep water marine (autochthonous, from bacterial degradation of sunk phytoplankton) CDOM pools, possibly comprised by autochthonous CDOM from bacterial degradation of sunk phytoplankton bloom remnants (not modeled in the current NYHOPS CDOM model). Carder *et al* (1989) have noted studies that point to weak covariance between chlorophyll and CDOM concentrations, and hypothesized that patches of marine humus are indicative of past primary productivity, not the present chlorophyll content of a patch.

The retrievals in 2006 included another flood of historic proportions in the area, the Susquehanna/Delaware Basin flood of June 28-29 2006, with widespread flooding and bank overtopping from upstate New York to North Carolina. Although its effects on the Hudson River and NJ Basins were smaller than elsewhere, it was a 5-year flood for the Hudson main stem, a 15-year flood for the Mohawk River, a major tributary of the Hudson at Cohoes, NY, and a significant event for the Raritan River at High Bridge. Although our satellite retrievals that might have included the impacts of that event on the coastal waters of the New York Bight Apex stop on July 4 2006 (July 7^{th} and 9^{th} have poor Apex coverage), that day, 5-6 days after rainfall, does indicate higher absorption estimates seemingly originating from a pool of CDOM within the Raritan estuary (Figure 11). This is seen both in the model, and the satellite retrievals, although the satellites indicate a more eastward advection than the model.

The second fortnight of October 2006 was quite wet, with significant rainfall and streamflows occurring around October 20^{th} and October 28^{th} 2006 (Figure 12). The two events seem to have combined in the lower NY Harbor, with high freshwater inputs from the Hudson (with a 10 day lag) and the Raritan manifested in the October 30^{th} and November 1^{st} retrievals (Figure 13). In that case, both model and satellite appear to show plume dispersal toward Long Island. Last but not least, the 6 retrievals in 2007, as well as the model results, indicate that the estuary plume moved largely to the South, along the NJ Coast. Although great variability among the model and each of the four retrieval algorithms exists with regard to the magnitude of CDOM absorption, the feature of a plume originating within NY Harbor and hugging the NJ shoreline is persistent in all estimates, from April 20, 2007 to May 6, 2007 (Figure 14).

In order to summarize the results of the satellite to NYHOPS CDOM model comparisons outside the NY/NJ Harbor, both model- and satellite-based absorption estimates were averaged over the quadrangle areas shown in Figure 15. The time series for each quadrangle are given in Figure 16. The variability among satellite retrieval algorithms in the NY Bight Apex quadrangle is striking, while the estimates are much more consistent away from land (NY Bight quadrangle). The GSM algorithm consistently provided the largest area of retrieval, but also the highest magnitudes for absorption estimates, especially in the locations that other algorithms did not converge, a questionable result. Conversely, the Carder algorithm (CAR) consistently provided the smallest areas of CDOM absorption retrievals, some of the smallest absorption magnitudes, and the closest absorption estimates to the NYHOPS CDOM model. The QAA algorithm estimates fell usually between the CAR and GSM algorithms. On the other hand, the Pan algorithm (PAN), an algorithm calibrated by its author for waters outside Delaware Bay, provided coverage almost as good as the GSM one, but significantly lower absorption estimates, and a usually good correspondence to the NYHOPS CDOM model.

IMPACT/APPLICATIONS

The new model has been linked to the automated NYHOPS forecasting system. It is currently providing allochthonous CDOM 48hr forecasts throughout the NYHOPS region, from the coast of Maryland to Nantucket Island, MA, to the northern end of the tidal Hudson River at Troy, NY, with the highest resolution provided within the NY/NJ Harbor and Long Island Sound. Advective-diffusive fluxes are provided by the new NYHOPS version 3 hydrodynamic module. Streamflow forecasts are coming from the Advanced Hydrologic Prediction Service and runoff is separated from base flow as aforementioned. Simulated allochthonous CDOM fluorescence (QSU), concentration (mg/L), and absorption at 355nm (m^{-1}) at the surface-most layer are plotted for each of the 48 hrs of the NYHOPS forecast period, then posted on the NYHOPS website for viewing: http://www.stevens.edu/maritimeforecast.

RELATED PROJECTS

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PUBLICATIONS

HONORS/AWARDS/PRIZES

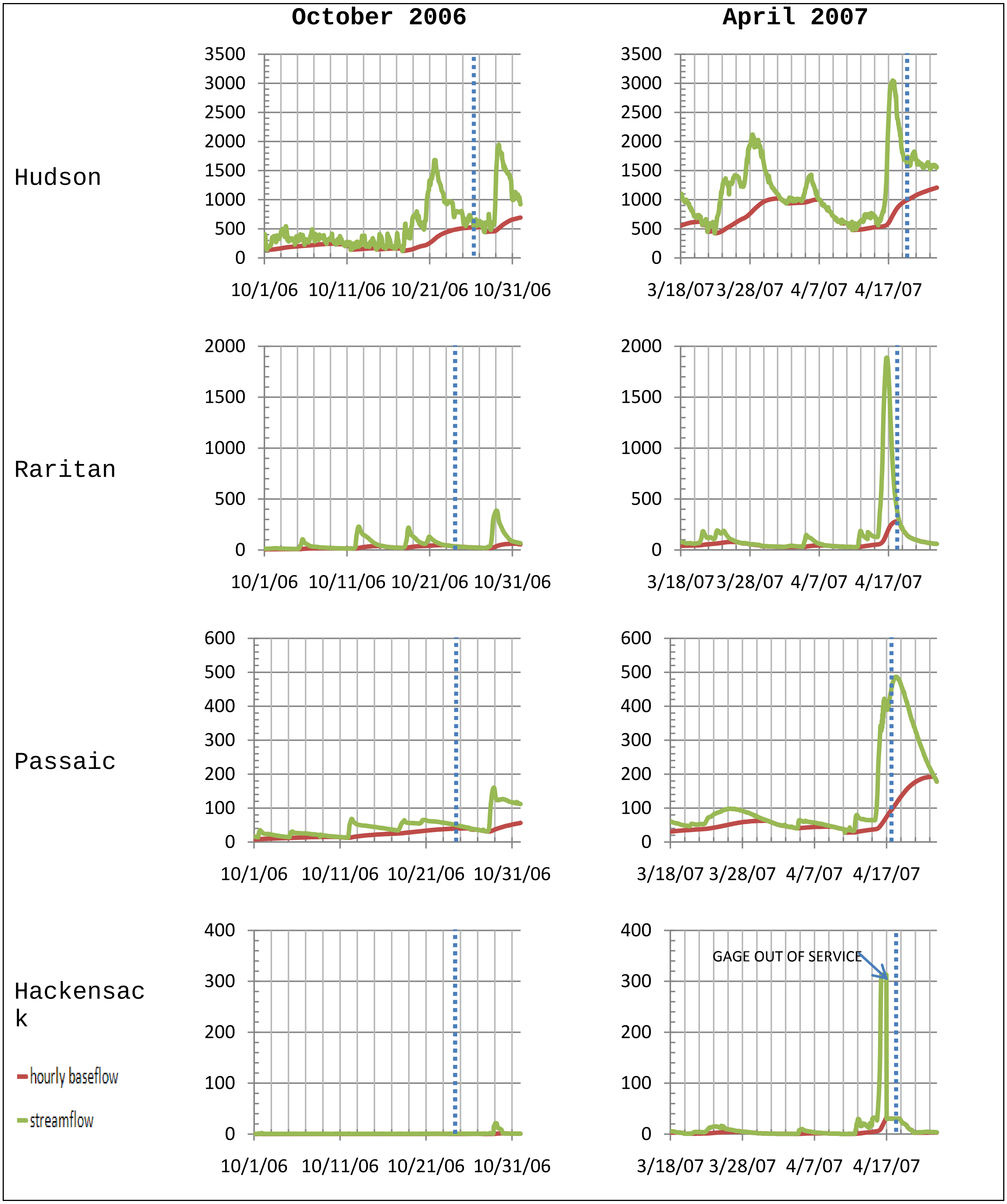


Figure 1. Hourly base flow separation of river inflows during the two sampling periods. Blue dotted lines indicate the days of sampling. Note that the Hackensack River gage malfunctioned due to record flooding during the "Tax Day" storm, as the water level submerged the equipment in the gage house (http://nj.usgs.gov/special/flood0407), providing unreliable flows for the April 2007 sampling period.

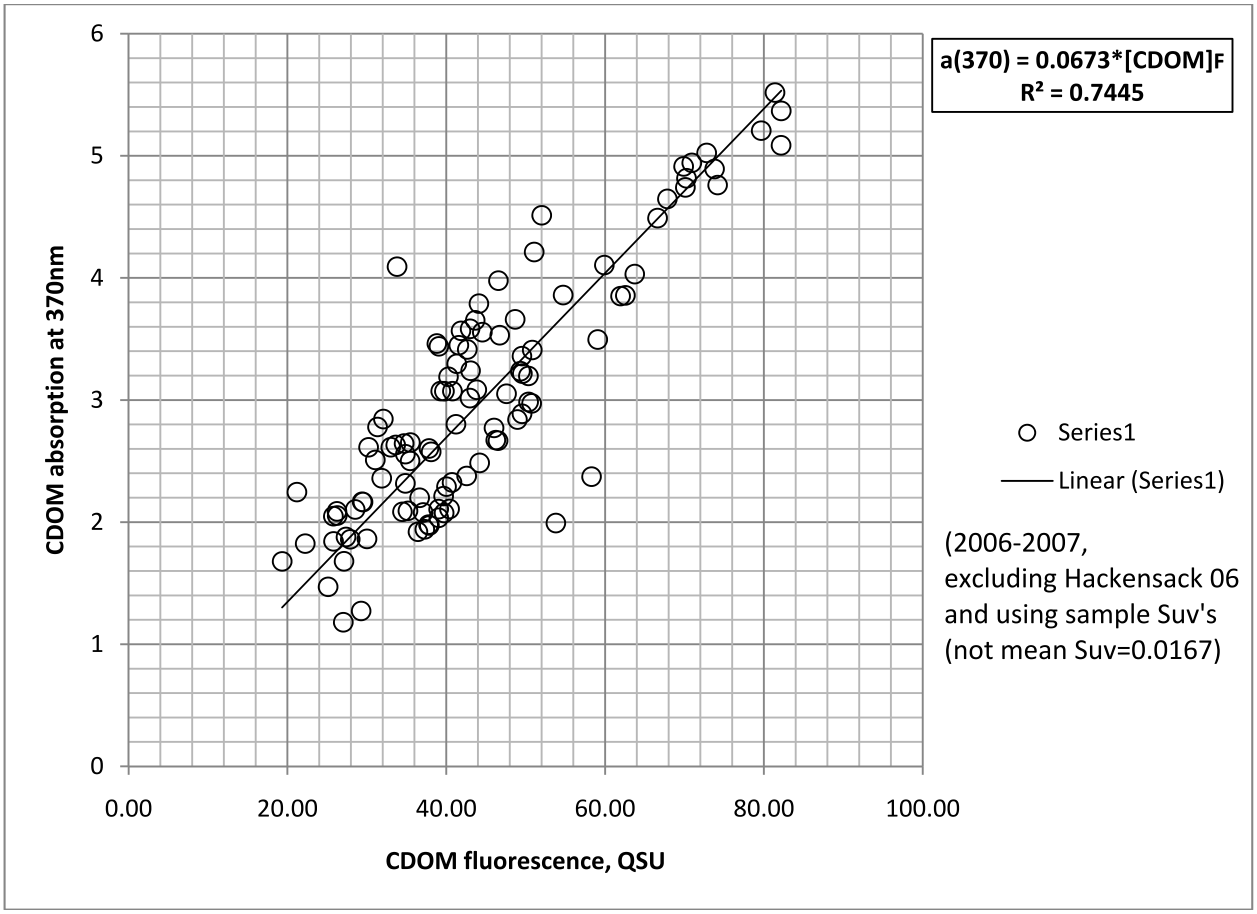


Figure 2. Regression of CDOM absorption at 370nm to CDOM fluorescence for 106 samples collected within the Hudson River and its tributaries in ECOShuttle surveys by the UMASS Boston team in 2006-2007 (data provided by Dr. Wei Huang, pers. comm.)

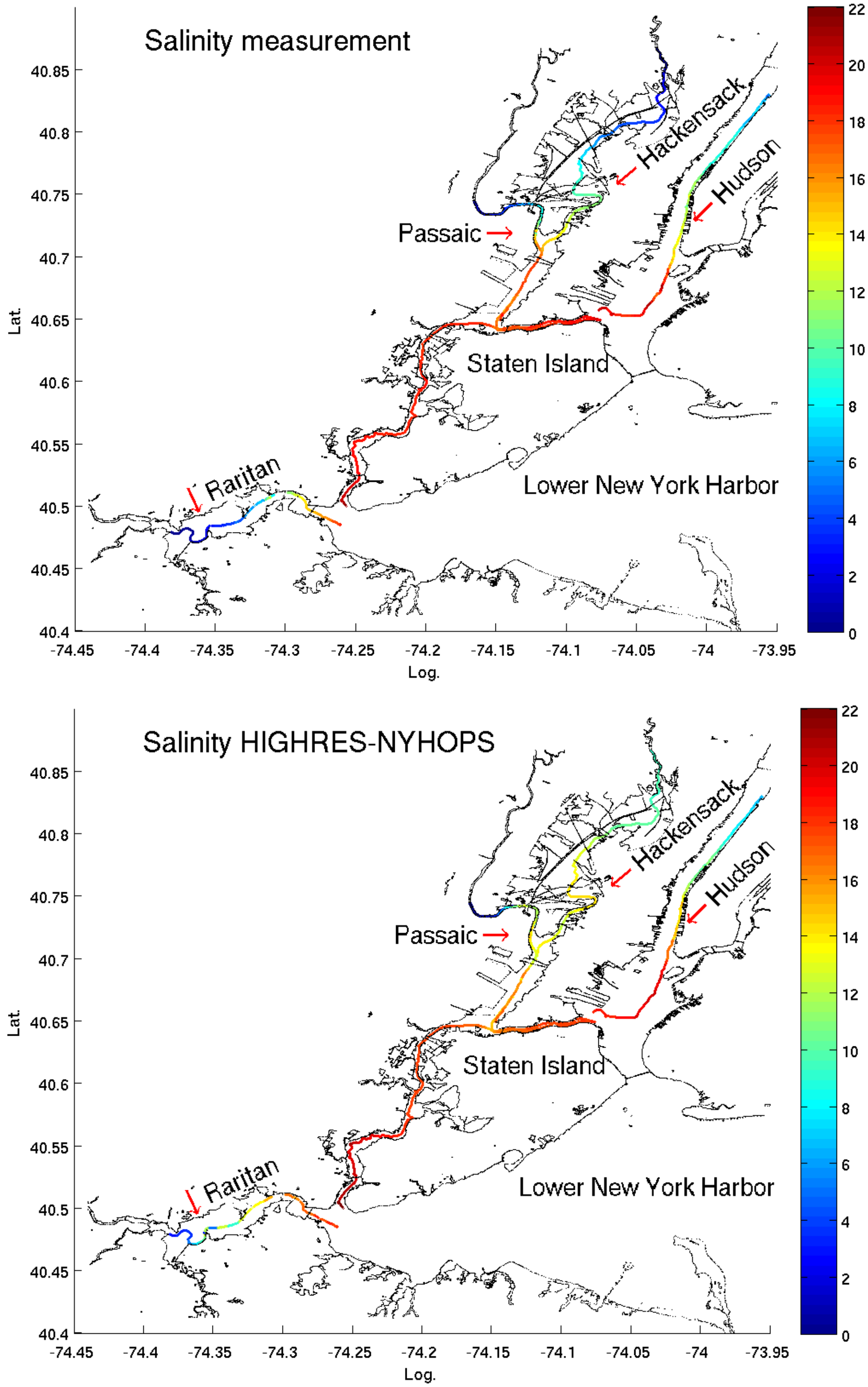
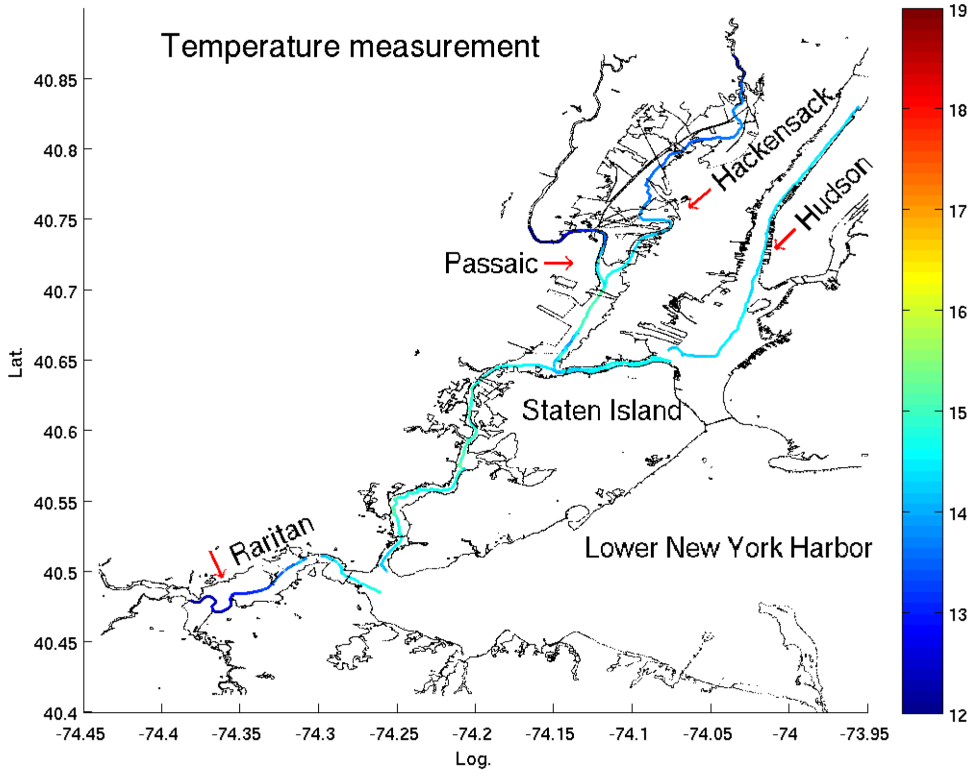


Figure 3. Along-track (Lagrangian) Salinity comparison between the ECOShuttle expedition of October 2006 and concurrent NYHOPS model results. Data were collected between Oct 23 and 26, 2006.



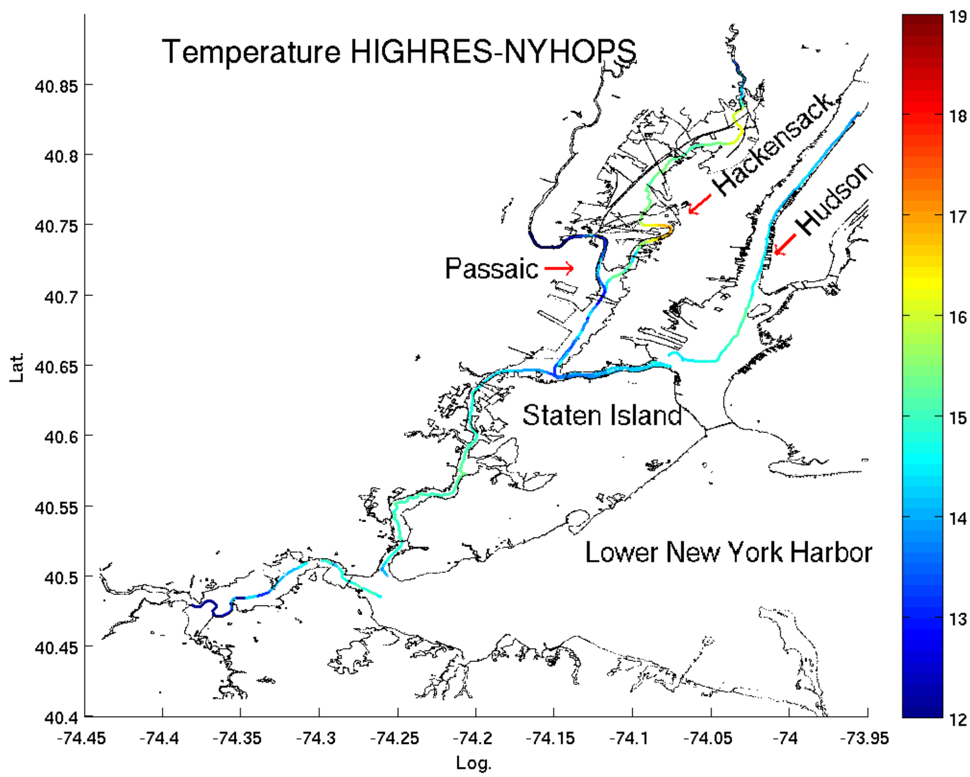


Figure 4. Along-track (Lagrangian) Water Temperature comparison between the ECOShuttle expedition of October 2006 and concurrent NYHOPS model results. Data collected between Oct 23 and 26, 2006.

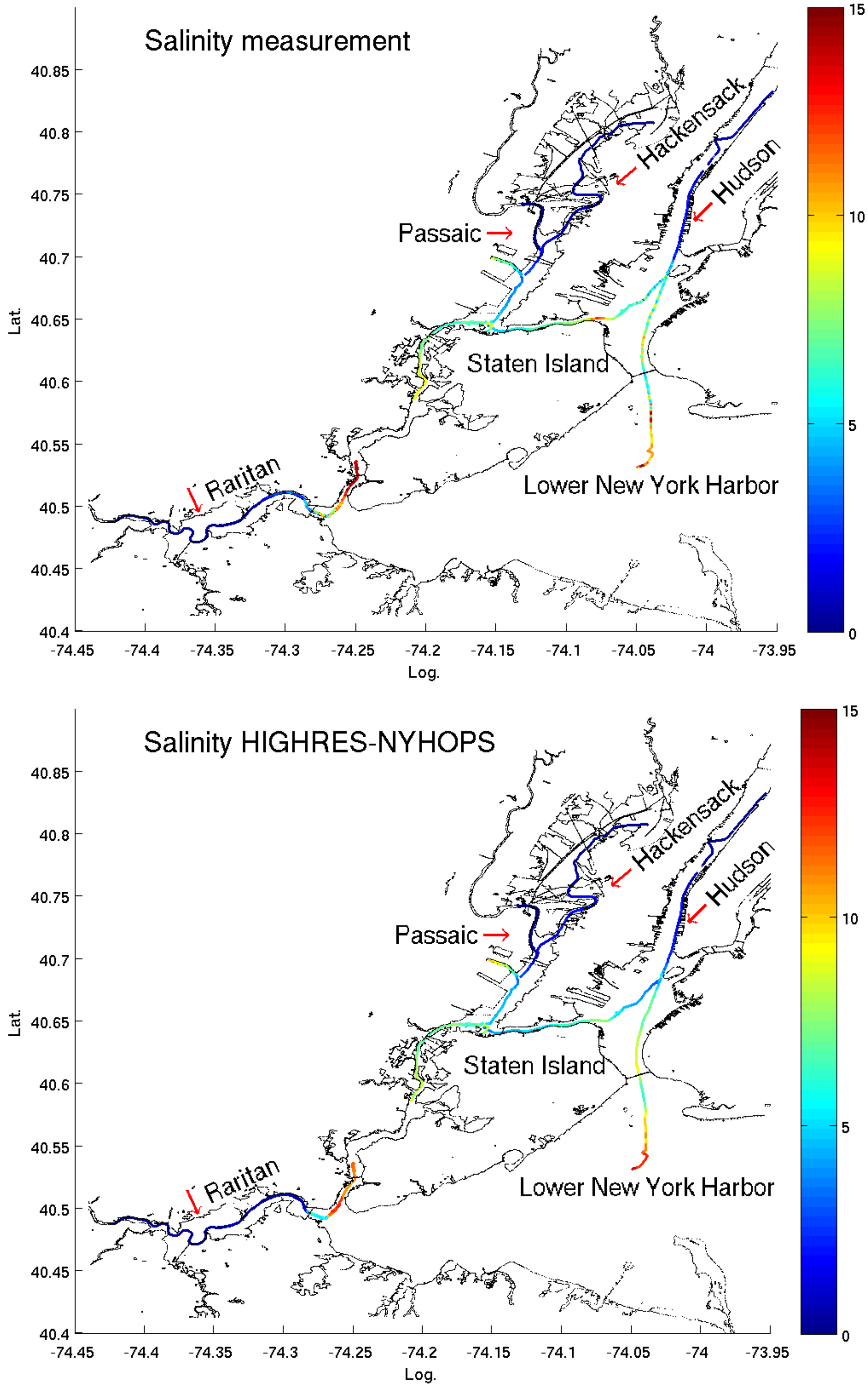


Figure 5. Along-track (Lagrangian) Salinity comparison between the ECOShuttle expedition of April 2007 and concurrent NYHOPS model results. Data collected between Apr 17 and 19, 2007.

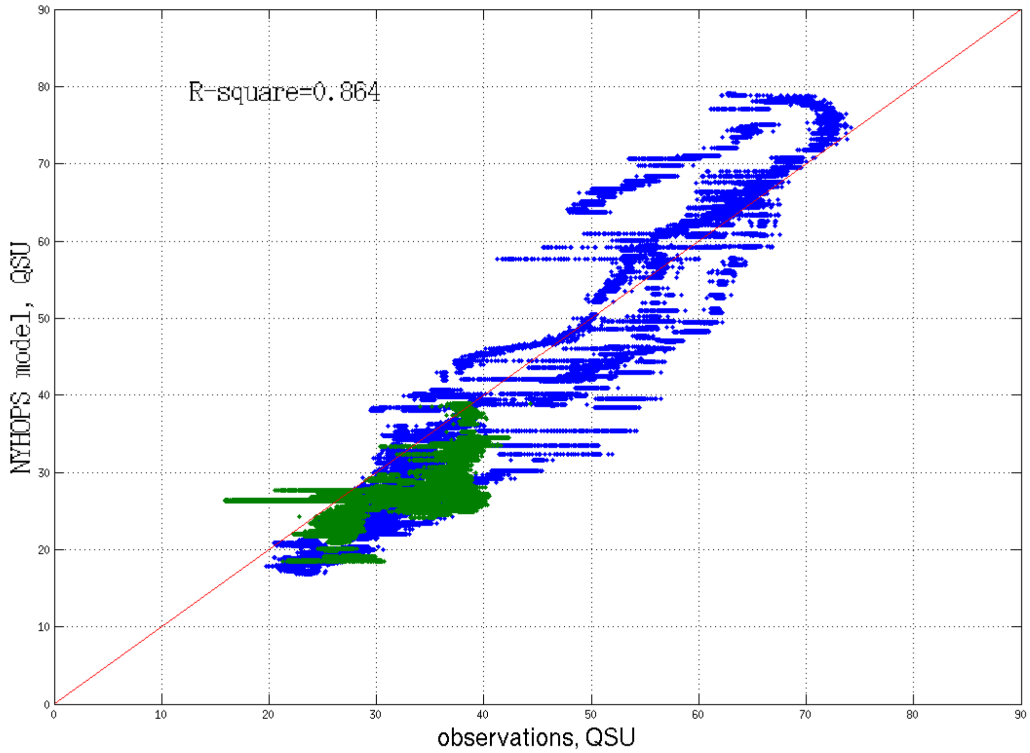


Figure 6. Correlogram of CDOM fluorescence among ECOShuttle observations and NYHOPS CDOM model results for transects in the NY/NJ Harbor Estuary between October 23 and 26, 2006 (blue dots), and April 17 and 19, 2007 (green dots). The red line indicates exact coincidence of NYHOPS model and observations.

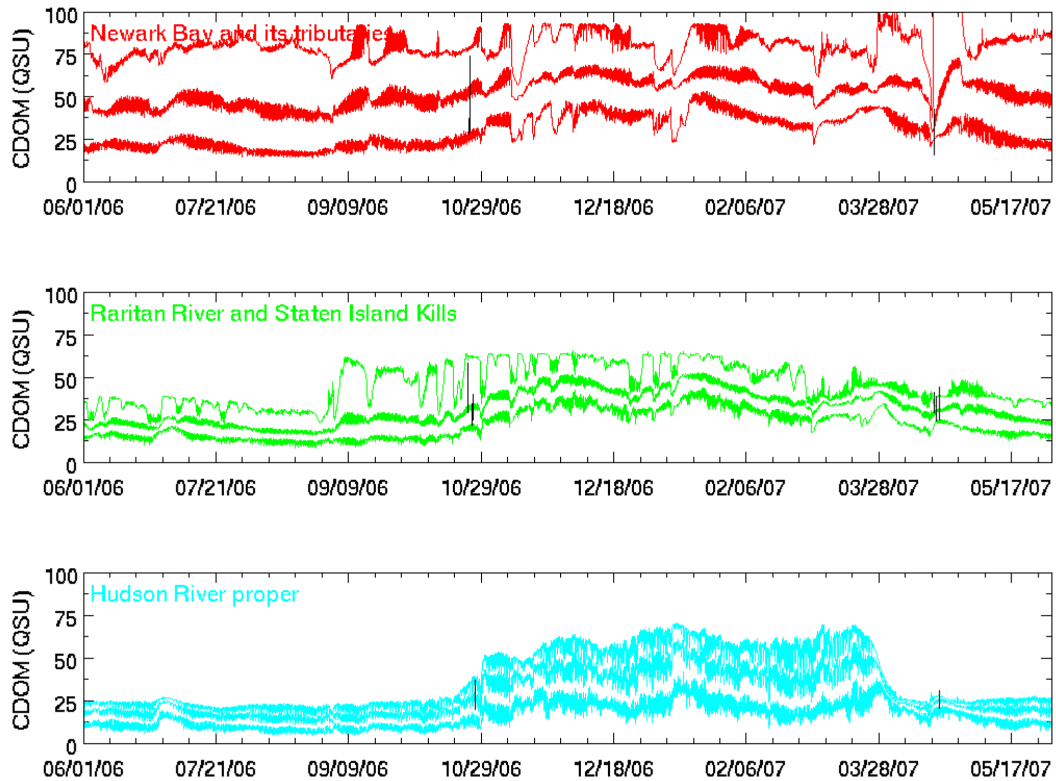


Figure 7. Time series comparisons of CDOM fluorescence among ECOShuttle observations and NYHOPS CDOM model results for transects in the NY/NJ Harbor for the period June 1, 2006 to May 31, 2007. Continuous timeseries indicate minimum, average, and maximum values of model results within the named region. Black bars indicate range of collected fluorescence data from ECOShuttle expeditions in the same region.

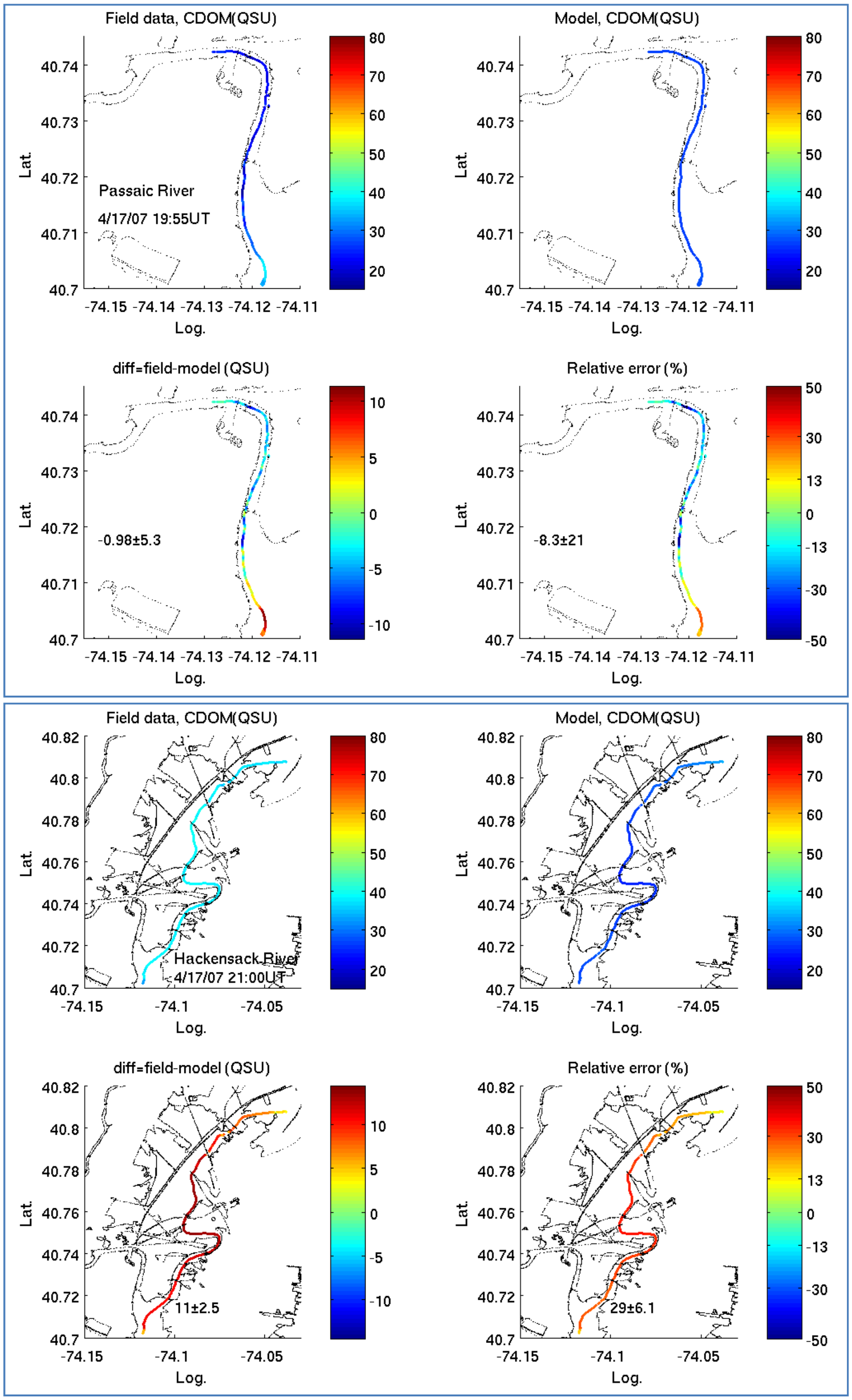


Figure 8. Examples of Lagrangian comparisons between ECOShuttle transect passes in 2007.

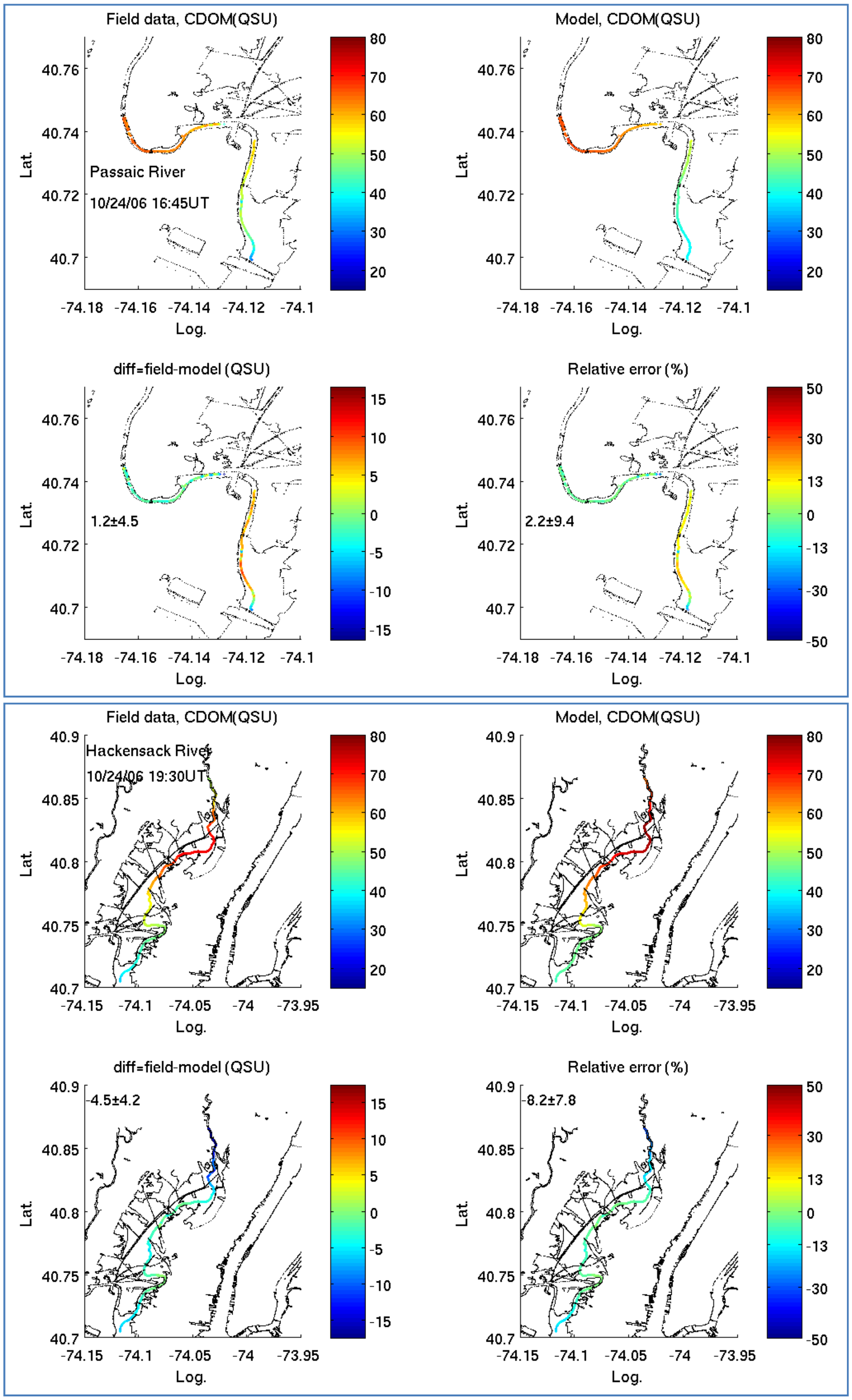


Figure 9. Examples of Lagrangian comparisons between ECOShuttle transect passes in 2006.

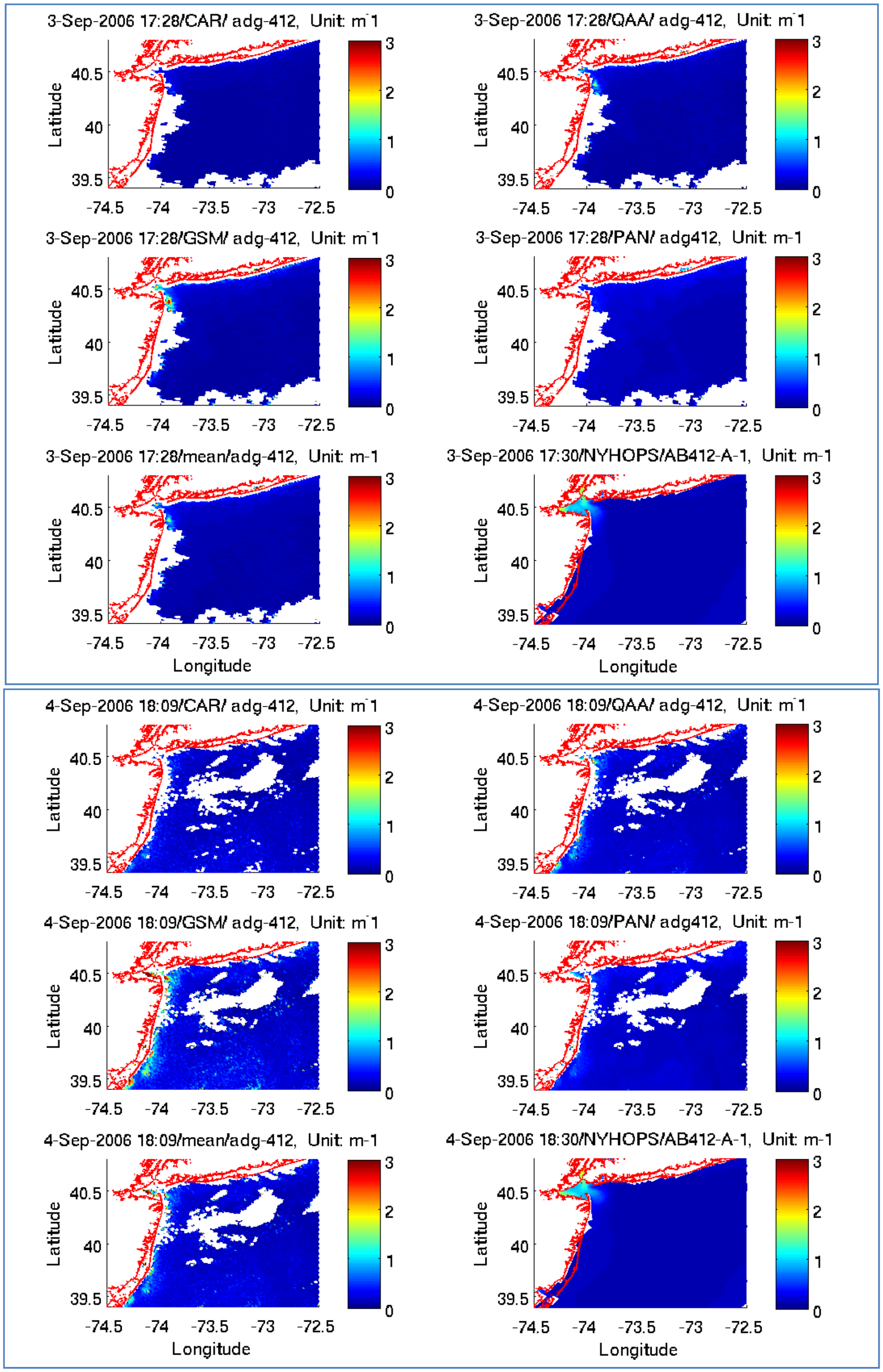


Figure 10. Satellite- and NYHOPS-derived CDOM absorption estimates before and after the passage of Tropical Storm Ernesto on September 3, 2006.

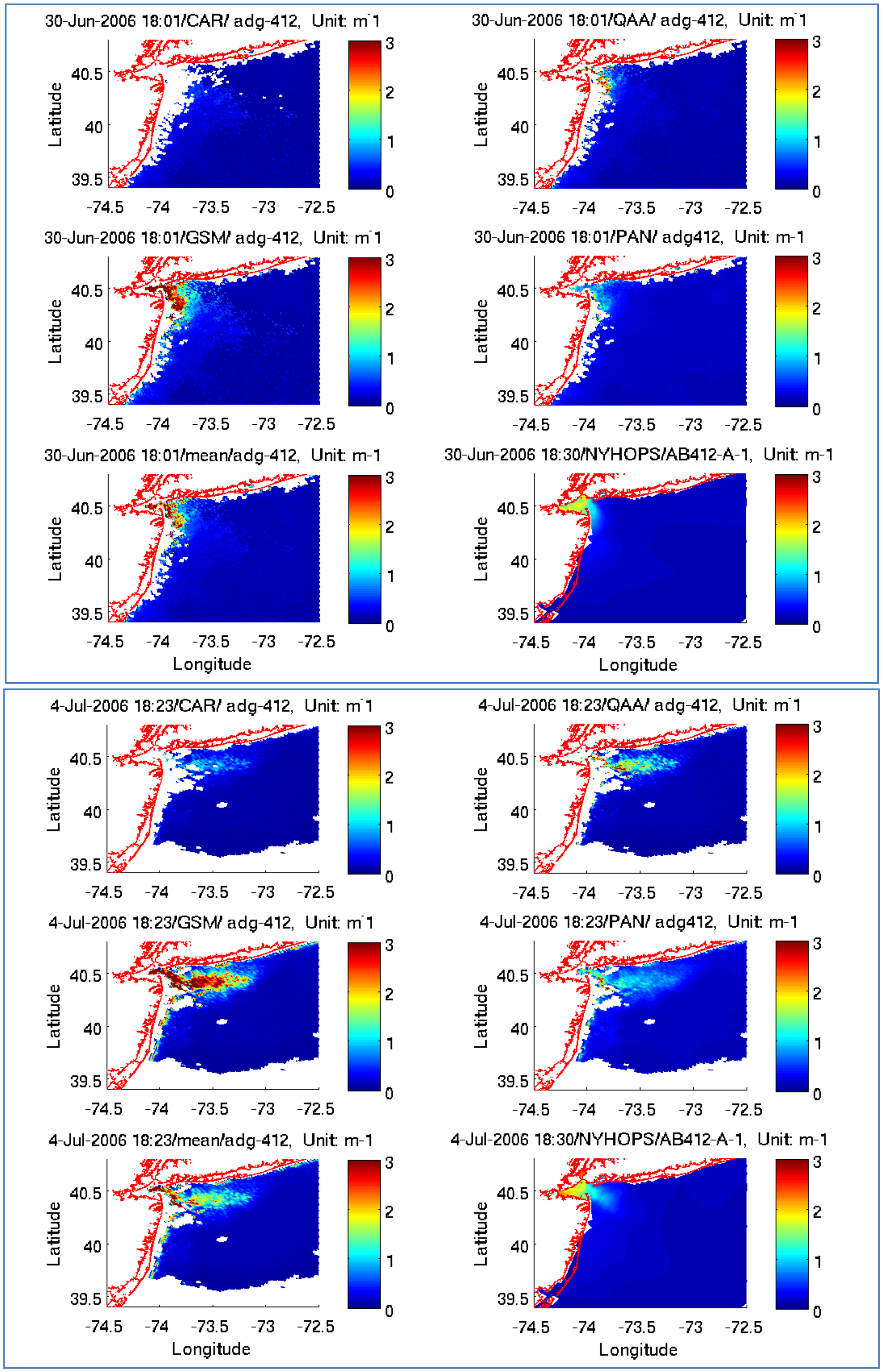


Figure 11. Satellite- and NYHOPS-derived CDOM absorption estimates days after the Delaware-Susquehanna Basin floods of June 28, 2006.

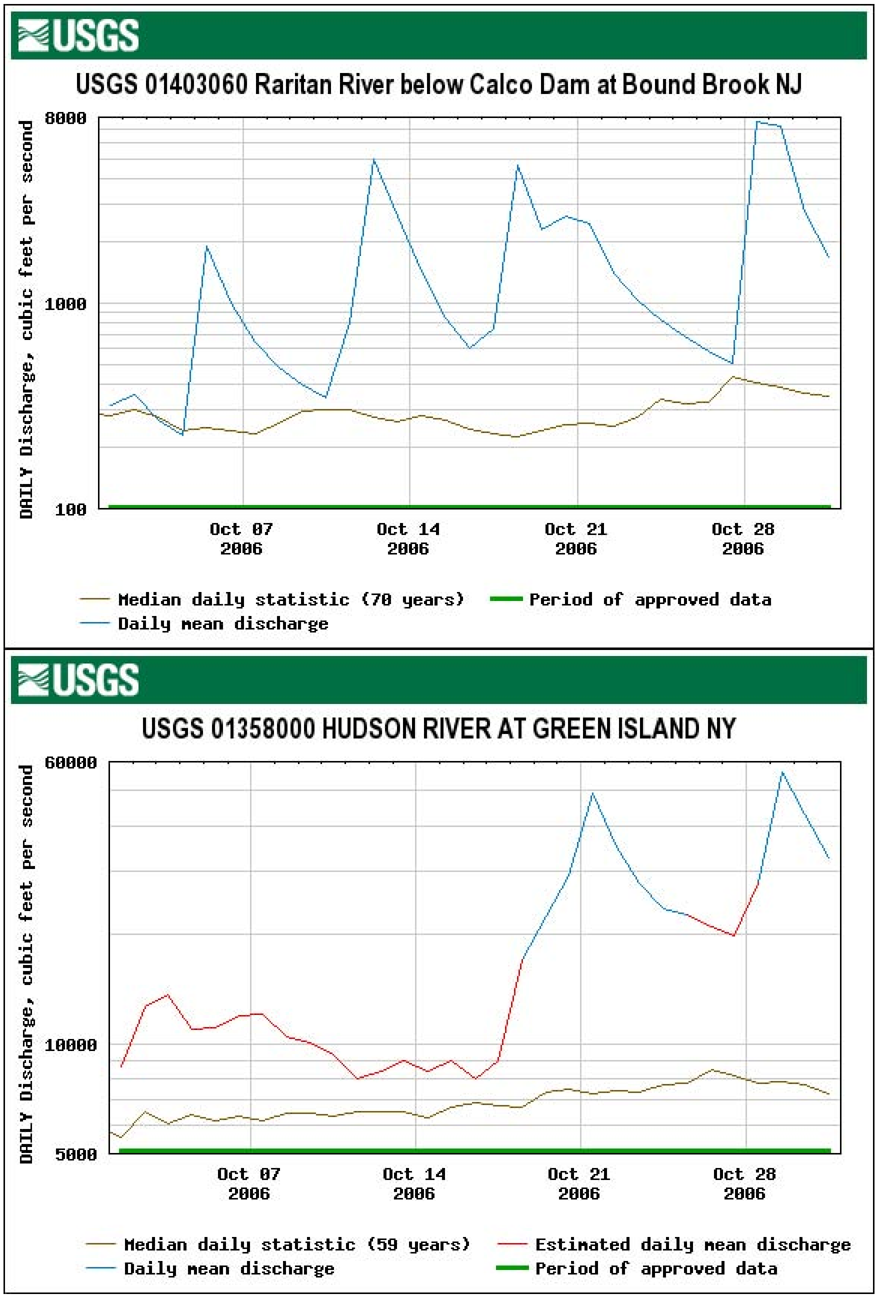


Figure 12. USGS streamflow records for the Raritan and Hudson Rivers, October 2006.

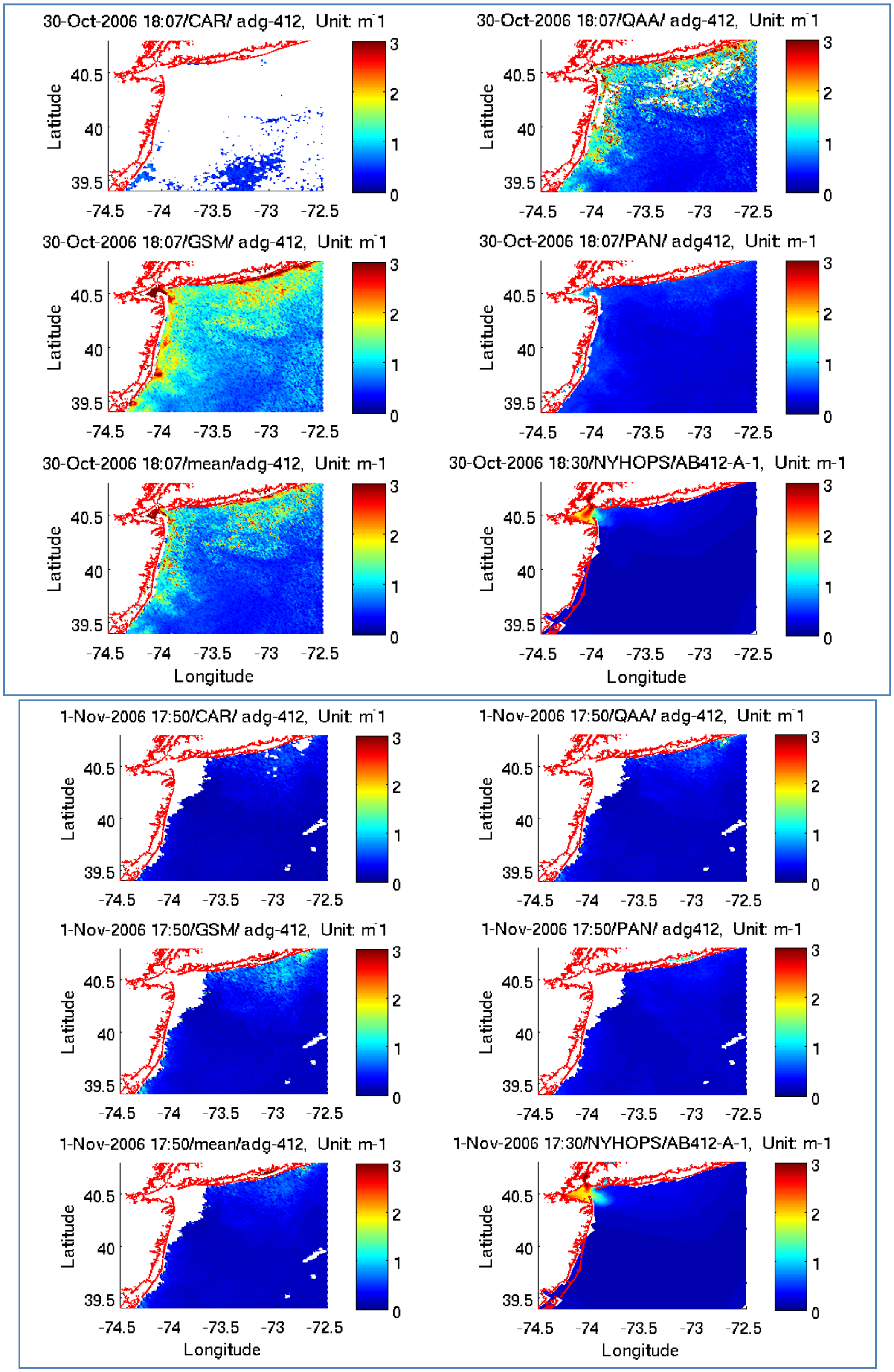


Figure 13. Satellite- and NYHOPS-derived CDOM absorption estimates for October 30 and November 1, 2006. Note plume dispersal toward Long Island captured by both the NYHOPS CDOM model and the satellite retrievals.

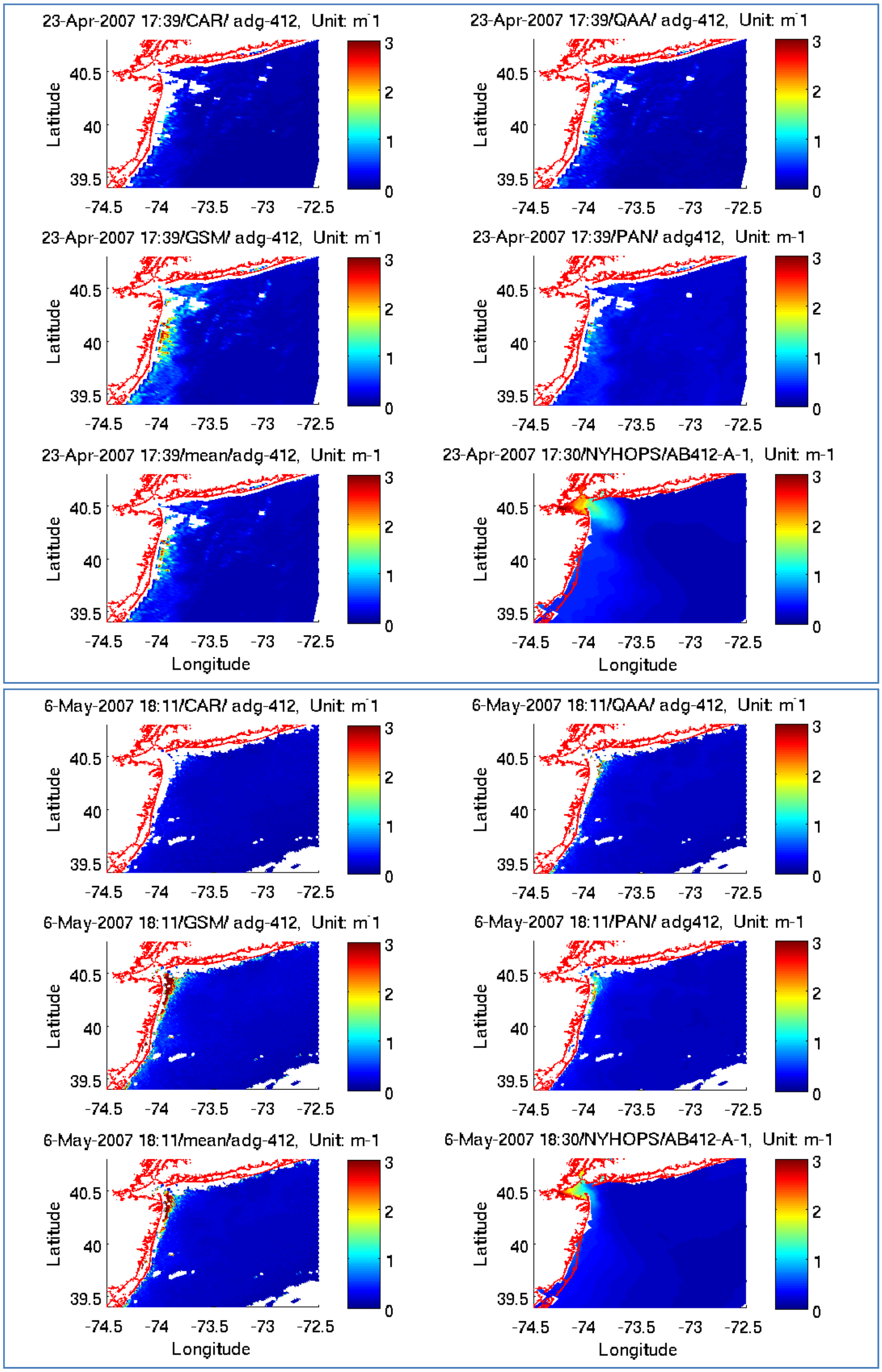


Figure 14. Satellite- and NYHOPS-derived CDOM absorption estimates days after the "tax day" flooding of April 15-16, 2007.

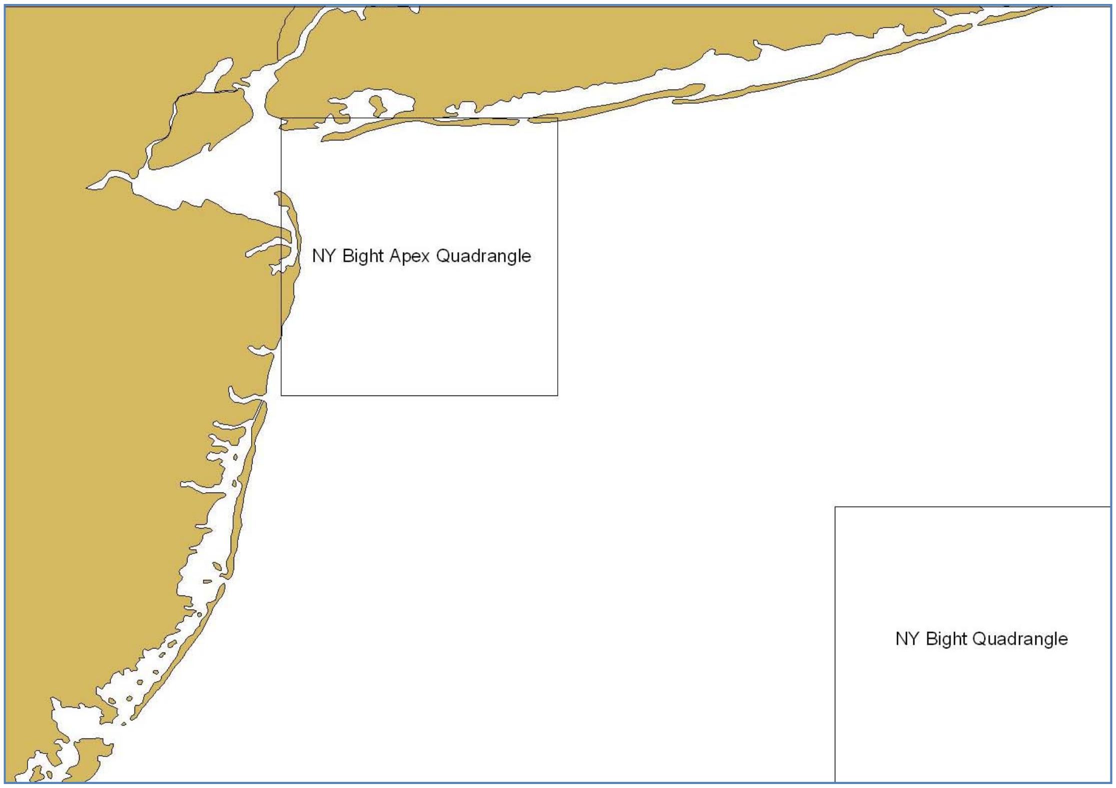


Figure 15. New York Bight Apex and New York Bight proper quadrangles used in Figure 16.

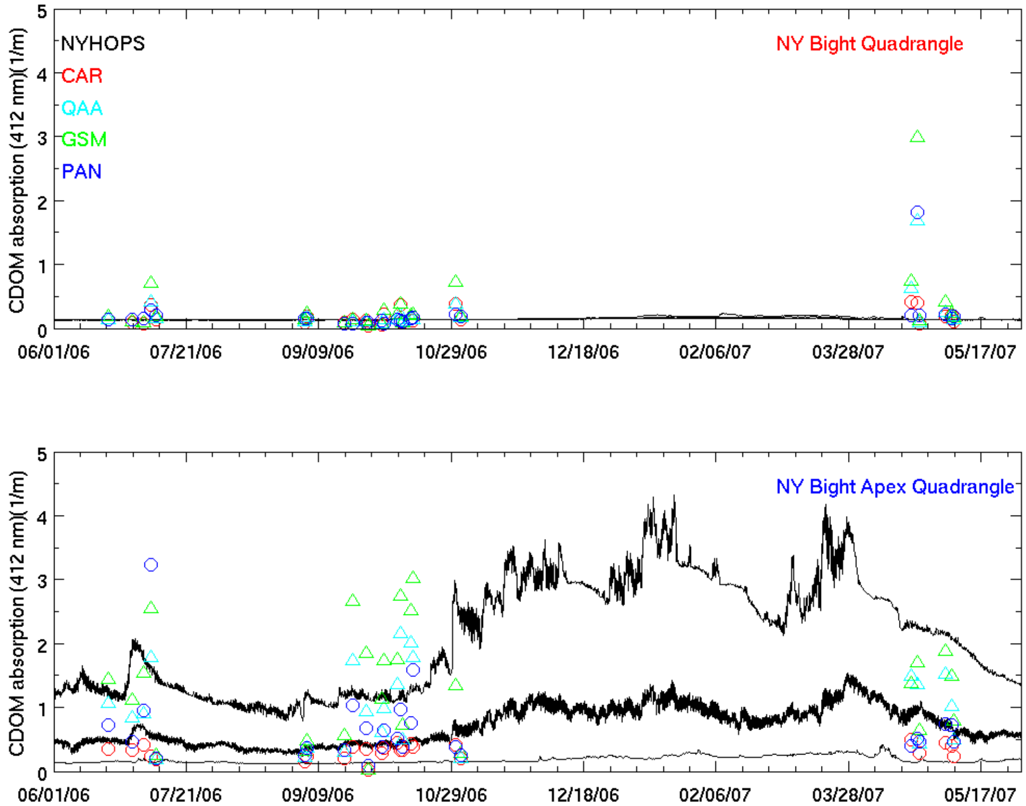


Figure 16. Time series comparisons of CDOM absorption at 412nm among four satellite retrieval algorithms [Carder (CAR, Carder et al 1999, Carder et al 2004), Quasi-Analytical (QAA, Lee et al 2002), Garver-Siegel-Maritorena (GSM, Garver et al 1997, Maritorena et al 2007), and Pan (PAN, Pan et al 2008)] and the NYHOPS CDOM model for the two regions shown in Figure 15. The continuous black lines indicate minimum, average, and maximum absorption estimates from the NYHOPS CDOM model.